v1: 27 July 2024

Review Article

Effect of Bromide on Livestock Development: A Review

Preprinted: 21 June 2024
Peer-approved: 27 July 2024

Qeios, Vol. 6 (2024)
ISSN: 2632-3834

Heike Lucht[1], **Norman Casey**[2]

1. Department of Animal Science, University of Pretoria, South Africa; 2. University of Pretoria, South Africa

Thyroid hormones are critical for the growth, development, and maintenance of the body. The review aims to consider the sources of bromide, elucidate the potential effects that bromide could have on the functioning of thyroid hormone, and to present the risks of exposure to and ingestion of bromide in livestock production.

Corresponding author: Heike Lucht, heike.lucht@up.ac.za

Introduction

This review refers to the term "bromide" (Br^-) as the negative univalent form of bromine according to the definition used by [1]. Br^- bonds readily with univalent positive ions such as sodium (Na^+) and potassium (K^+) to form sodium bromide (NaBr) or potassium bromide (KBr), or with the methyl cation (CH_3^+) to form methyl bromide.

The principal hormones essential for controlling developmental and metabolic processes are triiodothyronine (T_3) and thyroxine (T_4)[2]. In this review, these hormones are collectively and interchangeably referred to as thyroid hormones (TH). Br^- is ubiquitous in the environment and occurs naturally in water, soil, and air. Consequently, livestock and crops could be exposed to Br^- present in these sources. It is commonly accepted that Br^- has no defined biological role; hence, it is not listed as an essential trace element, and it was apparent that Br^- has previously been overlooked to a large extent. However, [3] demonstrated its essential role in the collagen IV structure of basal membranes (BM).

Br^- is known to be toxic, and the toxicity is dose-dependent[4]. Renal excretion is the major route for Br^- elimination from the body, which means urinary Br^- concentration is a good indicator of daily intake[5]. Therefore, Br^- is an essential trace element that could become toxic when the ingested quantity surpasses the excretion capacity of healthy kidneys[3][6].

It is well documented that brominated chemicals such as flame retardants[7] and polybrominated diphenyl ethers[8] that release Br^- are TH disruptors. One naturally occurring source of Br^- is NaBr, which dissociates into Na^+ and Br^- ions when present as water quality constituents (WQC) in groundwater. A WQC is any chemical element present in a water source that may be benign, beneficial, or toxic based on the type of element and its pharmacodynamics in the body.

 doi.org/10.32388/6QHY9S.3

Seawater contains 19345 mg/kg chloride (Cl^-)[9] and is also a reservoir for iodide (I^-)[10]. Inorganic Br^- commonly is highly water-soluble[11]. Br^- concentration is generally high in seawater at 65 mg/L[12]. Livestock produced in coastal regions may be exposed to Br^- naturally from the environment.

A large source of fresh water in agriculture is groundwater. The presence of inorganic WQC in groundwater is complex and is due to the geology, volcanic activity, pH, oxygen, degree of dissociation of WQC, and water sources replenishing the aquifers. Dissociated inorganic WQC vary in their physical properties as they are categorised in the periodic table.

Drawing water from aquifers changes the composition of the water. [13] reported that human-induced changes to flow systems resulted in the mobilisation of naturally occurring trace elements that could eventually exceed the no observed adverse effect level (NOAEL) of an element. The NOAEL is the concentration of an element that is deemed safe for the animal and is usually determined using the mouse model.

Higher concentrations of Br^- may occur in groundwater found in hot and dry climates[1], which is consistent with subtropical climatic regions in which extensive livestock farming dominates. Intrusion of seawater into freshwater aquifers may result in an increase in Br^- and Cl^- contents in groundwater.

Water is a key element in livestock production as it affects feed intake and milk production, as well as all other essential metabolic functions in the animal body. Groundwater is used in many areas of low rainfall, such as across southern Africa, or where a constant supply of water is required for livestock. The risk of groundwater is the potential exposure to physiologically adverse WQC[14].

The thyroid gland is the site of TH production. The thyroid gland forms during early embryogenesis. TH is essential for the normal growth and development of the foetus[15]. During embryonic development, TH ensures that the correct sequence of tissue development is followed in each organ[16] therefore, disruption of TH during embryogenesis restricts organ development.

[17] showed a differential response in the relative mass gain of the heart, liver, and brain of chicken embryos after acute exposure to 1 mg/L Br^- at the beginning of incubation, where the heart showed possible hypertrophic growth compared with the brain and liver. This has implications for broiler susceptibility to ascites in the post-hatch growth phase, owing to the role of heart capacity in the development of ascites.

Endocrine-disrupting chemicals (EDC) are chemicals that disrupt endocrine pathways within the body and cause adverse effects, and have been well-studied in human physiology[18]. One of the main targets of EDC is TH[18]. Thyroid-disrupting chemicals (TDC) are absorbed EDC that become thyrotoxic by specifically targeting TH homeostasis. The TDC could be organic compounds such as methyl bromide or seemingly benign inorganic compounds like NaBr or KBr. It was established that acute exposure to 1 mg/L Br^- at the beginning of incubation was toxic to chicken embryos[17].

The aim of this review was to present evidence of the occurrence of Br^- in nature, the mechanism of interaction with I^-, and to present the risks of exposure and ingestion of Br^- to livestock production.

Methods

The data incorporated in this review were from our own published research on water quality for livestock, interactions between Br^- and I^-, and the effect of Br^- on the development of chicken embryos. We assimilated data from an extensive review of literature using ScienceDirect, PubMed, and Google Scholar. These databases were chosen to provide a broader overview as they included peer-reviewed open access literature as well as literature from journals to which the academic institution was subscribed. The literature search also included a review of human case studies. All relevant literature was included regardless of the publishing date. Historical literature was included because basic principles were described and were deemed relevant in the current context. Keywords used included "bromide," "toxicity," "metabolism," "thyroid hormone," "hypothyroidism," "iodine interaction," and "halide interactions." These keywords were chosen to refine the literature search to focus attention on the interactions of Br^- with I^- and its role in TH production.

Discussion

[19] defined homeostasis as "a self-regulating process by which biological systems maintain stability while adjusting to changing external conditions." This definition allows us to understand the delicate physiological balance within the body, which may be disturbed so severely as to result in pathology. When the NOAEL of a drug or substance is exceeded, it may result in pathological conditions (adverse effects). An example of this is when a normally benign substance is present at concentrations that overwhelm the body's capacity to excrete sufficient quantities to maintain homeostasis.

A key component of optimal physiological functioning is the control of principal electrolytes and fluid balance within the body. This is because the composition of extra- and intracellular fluid determines the effectiveness of cellular metabolism. These key electrolytes include Na^+ and K^+, and halides such as I^- and Cl^-. I^- and Cl^- have clearly defined biological roles; however, the role of Br^- was previously unclear as it was not described as an essential element. [3] identified the essentiality of Br^- as a cofactor for peroxidasin-mediated crosslink formation in collagen IV scaffolds of BM using the *Drosophila* model. BM serve as mechanical support for epithelial cells, and BM integrity therefore influences the integrity of the tissue. When Br^- was fed to Br^- -deficient *Drosophila*, peroxidasin was once again able to form hypobromous acid (HOBr), which mediates cross-link formation[3]. This indicated that Br^- is an essential element. Hypochlorous acid (HOCl) also mediates cross-link formation, but peroxidasin was shown to use Br^- to catalyse the formation of sulfilimine bonds in the collagen IV scaffolds with 50,000-fold greater efficiency compared to Cl^-[3]. Another positive role of Br^- is in inflammatory reactions. The production of HOBr is important in innate immunity and physiologically important processes like apoptosis and cell signalling[6]. This has implications for the effectiveness of immune responses to disease exposure in animals that are already under physiological pressure due to the intense production expectations.

Concentrations of Cl^- and Br^- are present in a steady state in body fluids depending on intake and are readily excreted[11] to maintain fluid homeostasis.

The kidney must reabsorb the vast majority of the filtered load of Cl^- to maintain the steady state of Cl^- in the blood[20]. Cl^- plays a role in the control of the osmotic gradient between intra- and extracellular fluids, allowing absorption or excretion of elements, including hormones, from cells.

It was demonstrated that Br^- is primarily excreted by the kidney 4 h after intraperitoneal injection in rats[21]. Cl^- is preferentially excreted over Br^- in the kidneys[22][23], although [24] reported that the biological half-life of Br^- could be shortened by administering a surplus of NaCl. This points to an interaction between Cl^- and Br^- in the body water spaces. At physiologically normal NaCl concentrations, it would appear that Br^- toxicity may be diagnosable by the occurrence of clinical hypochloraemia.

Kidney anatomy and physiology are known to differ between species, and animals within species adapted to different regions. Br^- may cause kidney damage and also has the capacity to exacerbate kidney dysfunction. The U.S. Centres for Disease Control and Prevention (CDC)[25] reported that people surviving serious Br^- poisoning can develop kidney damage. [26] confirmed that 250 mg/kg NaBr administered to mice with a hereditary, progressive kidney disease, Alport syndrome (AS), exacerbated the existing renal dysfunction.

Serum Br^- concentration is difficult to quantify due to interference with I^- and Cl^-[27]. Inorganic Br^- dissolved in solution, originating either from water or feed, is absorbed by the gastrointestinal tract into the circulation[28]. I^- was shown to interact with Br^- by having an ameliorative effect on high concentrations of Br^- ingested by broilers[29].

Bromide dynamics in biological systems

The dynamics of Br^- in biological systems seem universal regardless of the method of entry into the body. When ^{82}Br was administered to Br^- -deficient rats by intraperitoneal injection, it was found that blood concentration values indicated equal distribution between cells and plasma, although the concentration was initially higher in the plasma[21]. The bioavailability of ingested Br^- as NaBr in Merino sheep was 92%, and the terminal half-life was 14 ± 3 days[30] This long half-life shows the possibility of Br^- accumulation in the body water spaces.

Ingested Br^- moves easily through the body water spaces by means of passive and active transport using Cl^- channels. Intracellular movement of Br^- via neuronal Cl^- channels is the mechanism by which Br^- functions as an anticonvulsant[31][32]. Br^- partitions in the body similarly to Cl^-[33].

Regulation of the hypothalamus-pituitary-thyroid (HPT) axis can be the target of TDC, affecting TH clearance in the liver and kidneys[7]. [34] administered NaBr to Wistar rats at 0, 300, 1200, 4800, or 19 200 mg/kg diet for 4 weeks and reported a dose-related replacement of Cl^- by Br^- in plasma and organs, where the highest dose level affected electrolyte balance. Similarly, when renal excretion of I^- is accelerated by excessive Br^-, it may influence the pool of exchangeable I^- in the thyroid gland[23].

It is an indisputable fact that Br^- has an effect on biological systems, as inorganic Br^- is widely used in pharmaceuticals, especially anticonvulsants in dogs and as a sedative in horses (e.g., KBr)[35][32]. The discontinuation of the routine use of KBr as a sedative in humans has reduced the incidence of chronic Br^- intoxication[35]. The distribution and dynamics of Br^- in the bodies of different animals, using chemical analytical methods and isotopic techniques utilising ^{82}Br, indicated that Br^- has thyrotoxic characteristics that cause hypothyroidism[36][21][37][33]. Br^- toxicity that causes hypothyroidism will disrupt normal physiological functioning in the animal body, due to the interaction of the HPT axis with other hormone axes in the body.

Homeostasis, growth, and tissue differentiation of an animal depend on TH[38]. The thyroid gland is a target organ of Br^-[39]. The most likely underlying cause of thyroid dysfunction and, subsequently, the observed HPT axis changes, is the interaction of Br^- with I^- uptake by the thyroid gland[40][41][42][43]. Severe disruption of TH synthesis by Br^- will result in hypothyroidism[44].

It was noted that high doses of NaBr in rats inhibited thyroid function, lowered TH levels, and increased thyroid-stimulating hormone (TSH) levels[41][40]. Subclinical hypothyroidism can be diagnosed when T_4 and T_3 levels are within normal ranges but TSH levels are elevated[18]. Increased TSH levels indicate the drive of the body to restore thyroid gland function, as controlled by feedback mechanisms in the HPT axis.

The tissue TH status depends on the TH secretion from the thyroid gland as well as on normal TH metabolism[45]. In birds, T_4 levels increase throughout the last week of embryonic development, reaching a peak at hatching, and the consistently low T_3 levels throughout incubation increase sharply when the hatched chick begins breathing independently[46].

Consequences of bromide ingestion

Inorganic Br^- was shown to influence broiler growth and feed efficiency negatively even after short-term exposure to a maximum concentration of 3 mg/L Br^- in drinking water[47]. Despite this being a relatively low concentration in comparison to values reported to range from 0-132 mg/L in the groundwater used for livestock[48], it was far above the recommended NOAEL of 0.01 mg/L that [17] had established using chicken embryos as a sentinel. This illustrated that Br^- is potentially toxic to actively growing poultry even at low concentrations.

Accumulation of Br^- in the liver[49] suggests the possibility of Br^- entering the human food chain in cases where the fifth quarter is a main source of protein for people. Another concern is that Br^- is readily transferred into milk[50] and this could affect the production performance of pre-weaned animals. [50] reported decreased feed and water intake in lactating rats, which resulted in depressed milk production in response to Br^- ingestion. Another concern is the direct exposure of humans to Br^- when milk from animals is consumed, posing an inadvertent risk of hypothyroidism in people.

Influence of Br on livestock production

I^- is an essential halide for the production of TH. In humans, it is completely absorbed from the gastrointestinal tract, where up to 30% is taken up by the thyroid gland from the plasma pool[5]. Up to 30% of I^- is eliminated by the kidneys in 10 h[5]. Renal excretion of I^- could occur similarly in mammalian livestock, although the clearance rate may depend on the species-specific anatomy of the kidneys.

Normal TH production requires tyrosine from thyroglobulin (TG) to be iodinated in the thyroid gland. Ninety-five percent of I^- is in organic forms (T4 and T3 protein complexes), leaving the remaining 5% as the inorganic form, I^-[5]. The level of I^- supply within the organism affects the degree to which Br^- may become thyrotoxic.

The formation of brominated TG is likely to occur when the Br^-/I^- ratio is high due to either I^- deficiency or high Br^- intake[51], in which case the Br^- becomes thyrotoxic.

Excessive Br^- has the potential to affect the exchangeable I^- pool in the thyroid gland by increasing the renal excretion of I^-[23]. This is noteworthy since an excess of Br^- in the plasma may manifest as a secondary I^- deficiency even when a sufficient quantity of I^- is ingested. The threshold level at which Br^- causes hypothyroidism has not yet been established.

In vertebrates, the role of TH is to control the growth and differentiation of nearly every organ[16][7]. Embryonic growth and development in chickens take 21 days to complete[52]. Thus, *in ovo* TDC exposure has a relatively short window period in which lasting negative effects are ingrained. This can affect differential organ development and hatchability.

[17] reported differential responses in relative organ mass gain with increasing concentrations of Br^-. The implications of this finding are notable as the chosen organs play an important role in whole-body functioning and are affected by TH.

Hatchability is the proportion of eggs that survive to the end of incubation to produce chicks.[17] reported that concentrations of 0.05, 0.5, and 1 mg/L Br^- negatively affected chick hatchability when administered into the albumen by *in ovo* injection prior to incubation under standard conditions.[17] reported a high negative correlation (R^2= -0.92) between increasing concentrations of Br^- and the percentage of embryo survival, and a high positive correlation (R^2 = 0.82) between increasing concentrations of Br^- and the percentage of embryo mortality. The effect of Br^- exposure on hatchability can therefore present economic consequences for the livestock industry. In mammals, the variation in gestation length between species will affect the time the fetus is exposed to Br^- ingested by the pregnant dam. Differences in placentation between species may affect the transplacental transfer of Br^- to the developing fetus.

The Br^- concentrations used by [17] were low compared to the 3 mg/L used by [47] [29]. Further research is required to elucidate the effect of Br^- on the foetal development of livestock. This is essential as TH is required for skeletal muscle development, contractile function, and muscle regeneration[53], and foetal programming of muscle growth and development occurs at a critical stage of

gestation. Br^--induced hypothyroidism will affect the attainment of production goals in animals raised for food.

Body mass accretion is the cornerstone of livestock production, and T_3 controls somatotropin (GH) and insulin-like growth factor I (IGF-I) activities, which influence body growth[54]. Increased plasma T_3 concentration will increase metabolic rate (MR)[55] and stimulate increased mitochondrial oxygen consumption[56]. Furthermore, T_3 is involved in cell proliferation[56]. In avian embryogenesis, the sequence of cell proliferation, differentiation, and maturation of each tissue and organ is controlled by TH[16]. The chronological sequence of embryological tissue development is nervous tissue > bone > muscle > fat.

A higher growth rate, typical of broiler chickens, results in a higher MR and thus greater turnover of T_4 to T_3 in tissues, which predisposes fast-growing birds to lower thermal stress tolerance when plasma TH concentration is insufficient to support a higher MR[57]. A similar challenge may be seen in beef and lamb production, where a high growth rate is a production goal. Hypothyroidism resulting from exposure to a TDC such as Br^- will slow the growth rate of the animals.

Increased thyroid gland activity in late embryogenesis increases the plasma T_4 concentration necessary to support fast growth in the latter stages of incubation in birds[57]. The process by which T_4 is formed in the thyroid gland can be disrupted by competition between I^- and Br^-, resulting in hypothyroidism.

Hypothyroidism can affect the structure and function of the liver directly. A decreased concentration of T_3 in the hepatocytes led to decreased liver metabolism[45]. In the case of Br^- toxicity, a decreased production of TH in the liver when Br^- replaces I^- during cellular TH production would impair liver function. This is crucial given the role that the liver plays in the filtration and distribution of nutrients from digestion, and the importance of such nutrients for development and maintenance.

Exposure to Br^- at concentrations exceeding the NOAEL may affect TH production, which limits animal production efficiency by inducing a hypothyroid state in the body. Mitigation strategies require the timely identification of Br^- toxicosis, and there are different potential options to mitigate the effect of Br^- on livestock production. Further research on the possible mitigation strategies and their effectiveness is needed.

Conclusion

The evidence presented in this review suggests that Br^- is an essential element for tissue development. It further suggests that Br^- ingested from the environment, such as groundwater, can satisfy the requirements for Br^- in BM formation and immune response. Conversely, it was shown that Br^- has the capacity to act as a TDC by interfering directly with TH production by interacting with I^-, when the ingested quantity exceeds the NOAEL.

The NOAEL of 0.01 mg/L was proposed in the South African Water Quality Guidelines for Livestock Watering and validated using the chicken embryo model. 3 mg/L was reported to affect the feed intake and growth of broiler

chickens. Further research is required to establish the NOAEL of Br^- in ruminant livestock, as well as the effect of Br^- ingestion on livestock in different physiological stages of production.

Statements and Declarations

Funding

National Research Foundation, South Africa, incentive grant to NHC, reference: PR-IFR180205310035/UID96806, and University of Pretoria Physiology Grant: NHC, reference A09038

Conflicts of interest

There was no conflict of interest.

References

1. a, b *Winid B (2015). "Bromine and water quality - Selected aspects and future pers pectives." Appl Geochemistry. **63**:413–435. doi:10.1016/j.apgeochem.2015.10.004.*
2. ^ *Velasco I, Bath SC, Rayman MP (2018). "Iodine as Essential Nutrient during the First 1000 Days of Life." Nutrients. **10**(3):290–305. doi:10.3390/nu10030290.*
3. a, b, c, d, e *McCall AS, Cummings CF, Bhave G, Vanacore R, Page-McCaw A, Hudson BG (2014). "Bromine Is an Essential Trace Element for Assembly of Collagen IV Sc affolds in Tissue Development and Architecture." Cell. **157**(6):1380–1392. doi:10.101 6/j.cell.2014.05.009.*
4. ^ *Baird-Heinz HE, Van Schoick AL, Pelsor FR, Ranivand L, Hungerford LL (2012). "A systematic review of the safety of potassium bromide in dogs." J Am Vet Med A ssoc. **240**(6):705–715. doi:10.2460/javma.240.6.705.*
5. a, b, c, d *Novakova G, Bonev P, Duro M, Azevedo R, Couto C, Pinto E, Almeida A (20 23). "Serum Iodine and Bromine in Chronic Hemodialysis Patients - An Observati onal Study in a Cohort of Portuguese Patients." Toxics. **11**(3):247. doi:10.3390/toxic s11030247.*
6. a, b *Vlasova II (2018). "Peroxidase activity of human hemoproteins: Keeping the fir e under control." Molecules. **23**(10):2561. doi:10.3390/molecules23102561.*
7. a, b, c *Jugan ML, Levi Y, Blondeau JP (2009). "Endocrine disruptors and thyroid hor mone physiology." Biochem Pharmacol. **79**(7):939–947. doi:10.1016/j.bcp.2009.11.0 06.*
8. ^ *Crofton KM, Craft ES, Hedge JM, Gennings C, Simmons JE, Carchman RA, Carter HW Jr, DeVito MJ (2005). "Thyroid-Hormone–Disrupting Chemicals: Evidence for Dose-Dependent Additivity or Synergism." Environ Health Perspect. **113**(11):1549–1554. doi:10.1289/ehp.81.*
9. ^ *Anthoni JF (2006). "The chemical composition of seawater." Magnesium. **2701** (96):e9062.*
10. ^ *Ito K, Hirokawa T (2009). "Iodine and iodine species in seawater: Speciation, dis tribution and dynamics." In: Comprehensive Handbook of Iodine: Nutritional, Bio chemical, Pathological and Therapeutic Aspects. Vol. 17. pp. 83–91.*
11. a, b *World Health Organization (2009). "Bromide in Drinking-water: Background document for development of WHO Guidelines for Drinking-water quality." Worl d Health Organization.*

12. ^ *Magazinovic RS, Nicholson BC, Mulcahy DE, Davey DE (2004). "Bromide levels in natural waters: its relationship to levels of both chloride and total dissolved solids and the implications for water treatment." Chemosphere.* **57**(4):329–335. doi:10.1016/j.chemosphere.2004.04.056.
13. ^ *Ayotte JD, Szabo Z, Focazio MJ, Eberts SM (2011). "Effects of human-induced alteration of groundwater flow on concentrations of naturally-occurring trace elements at water-supply wells." Applied Geochemistry.* **26**(5):747–762. doi:10.1016/j.apgeochem.2011.01.033.
14. ^ *Meyer JA, Casey NH (2012). "Establishing risk assessment on water quality for livestock." Animal Frontiers.* **2**(2):44–49. doi:10.2527/af.2012-0041.
15. ^ *Forhead AJ, Fowden AL (2014). "Thyroid hormones in fetal growth and prepartum maturation." J Endocrinol.* **221**(3):R87–R103. doi:10.1530/JOE-14-0025.
16. a, b, c *Darras VM (2019). "The role of maternal thyroid hormones in avian embryonic development." Front Endocrinol.* **10**(66):1–10. doi:10.3389/fendo.2019.00066.
17. a, b, c, d, e, f, g *Lucht HL, Casey NH, Sawosz E (2018). "Survival and development of embryos of Gallus gallus domesticus treated with inorganic bromide." South African Journal of Animal Science.* **48**(3):583–589. doi:10.4314/sajas.v48i3.19.
18. a, b, c *Chen S, Yu M, Yao Y, Li Y, He A, Zhou Z, Pan L, Xiao N, Luo H, Sun H (2024). "Thyroid Hormone Biomonitoring: A Review on Their Metabolism and Machine-Learning Based Analysis on Effects of Endocrine Disrupting Chemicals." Environment & Health.* **2**(6):350–372. doi:10.1021/envhealth.3c00184.
19. ^ *Billman GE (2020). "Homeostasis: The Underappreciated and Far Too Often Ignored Central Organizing Principle of Physiology." Front Physiol.* **11**:200. doi:10.3389/fphys.2020.00200.
20. ^ *Edwards JC (2012). "Chloride transport." Compr Physiol.* **2**(2):1061–1092. doi:10.1002/cphy.c110027. PMID 23798296.
21. a, b, c *Cole BT, Patrick H (1958). "Tissue uptake and excretion of bromine-82 by rats." Archives of Biochemistry and Biophysics.* **74**(2):357–361. doi:10.1016/0003-9861(58)90006-7.
22. ^ *Pavelka S, Babicky A, Vobecky M, Lener J, Svandová E (2000). "Bromide Kinetics and Distribution in the Rat. I.: Biokinetics of 82Br-Bromide." Biological Trace Element Research.* **76**(1):57–66. doi:10.1385/bter:76:1:57.
23. a, b, c *Pavelka S (2004). "Metabolism of bromide and its interference with the metabolism of iodine." Physiol Res.* **53**(Suppl 1):S81–S90. PMID 15119938.
24. ^ *Czerwinski AL (1958). "Bromide Excretion as Affected by Chloride Administration." Journal of the American Pharmaceutical Association (Scientific ed.).* **47**(7):467–471. doi:10.1002/jps.3030470703.
25. ^ *U.S. Centers for Disease Control and Prevention (CDC). "Facts about Bromide." Emergency Preparedness and Response. https://emergency.cdc.gov/agent/bromine/basics/facts.asp#:~:text=People%20who%20survive%20serious%20bromine,damage%20from%20low%20blood%20pressure. Accessed 28 May 2024.*
26. ^ *Yokota T, Omachi K, Suico MA, Kojima H, Kamura M, Teramoto K, Kaseda S, Kuwazuru J, Shuto T, Kai H (2017). "Bromide supplementation exacerbated the renal dysfunction, injury and fibrosis in a mouse model of Alport syndrome." PLoS ONE.* **12**(9):e0183959.
27. ^ *Rayamajhi S, Sharma S, Iftikhar H (2023). "Unexplained Bromide Toxicity Presenting as Hyperchloremia and a Negative Anion Gap." Cureus.* **15**(3):e36218. doi:10.7759/cureus.36218.
28. ^ *Braam RL, van Uum SH, Russel FG, Swinkels DW, Thien T (2006). "Bromide as a marker to measure adherence to drug therapy." Eur J Clin Pharmacol.* **62**(4):285–

290. doi:10.1007/s00228-006-0103-5.

29. ^a, ^b du Toit J, Casey NH (2012). "Iodine as an alleviator of bromine toxicity in thyro id, liver and kidney of broiler chickens." Livestock Science. **144**(3):269–274. doi:10. 1016/j.livsci.2011.12.011.
30. ^ Quast TA, Combs MD, Edwards SH (2015). "Pharmacokinetics of bromide in adu lt sheep following oral and intravenous administration." Aust Vet J. **93**(1-2):20–25. doi:10.1111/avj.12285.
31. ^ Moeser A, Steinberg SA (2015). "Anticonvulsants." In: Silverstein DC, Hopper K, e ditors. Small Animal Critical Care Medicine. 2nd ed. W.B. Saunders. pp. 872–876. doi:10.1016/B978-1-4557-0306-7.00166-5.
32. ^a, ^b Gouveia Di, Mandigers P, Cherubini CB (2024). "Bromide: the good, the bad, an d the ugly of the oldest antiseizure medication." Front Vet Sci. **11**. doi:10.3389/fvet s.2024.1433191.
33. ^a, ^b Ullberg S, Ewaldsson B (1964). "Distribution of Radio-Iodine Studied by Whole -Body Autoradiography." Acta Radiologica: Therapy, Physics, Biology. **2**(1):24–32. doi:10.3109/02841866409134127.
34. ^ Van Logten MJ, Wolthuis M, Rauws AG, Kroes R (1973). "Short-term toxicity stud y on sodium bromide in rats." Toxicology. **1**(4):321–327. doi:10.1016/0300-483X(73) 90038-3.
35. ^a, ^b Environment Agency (2005). "Science Report A Review of the Toxicity and En vironmental Behaviour of Bromine in Air." Almondsbury, Bristol: Environment Ag ency.
36. ^ Mason MF (1936). "Halide distribution in body fluids in chronic bromide intoxic ation." J Biol Chem. **113**:61–73.
37. ^ Hellerstein S, Kaiser C, Darrow DD, Darrow DC (1960). "Distribution of bromide a nd chloride in the body." J Clin Investig. **39**:282–287. doi:10.1172/JCI104038.
38. ^ van der Spek AH, Fliers E, Boelen A (2017). "The classic pathways of thyroid hor mone metabolism." Molecular and Cellular Endocrinology. **458**:29–38. doi:10.101 6/j.mce.2017.01.025.
39. ^ Suwanlaong K, Phanthumchinda K (2008). "Neurological manifestation of met hyl bromide intoxication." J Med Assoc Thail. **91**(3):421–426. PMID 18575299.
40. ^a, ^b Loeber JG, Franken MAM, van Leeuwen FXR (1983). "Effect of sodium bromide on endocrine parameters in the rat as studied by immunocytochemistry and radi oimmunoassay." Food and Chemical Toxicology. **21**(4):391–404. doi:10.1016/0278 -6915(83)90093-5.
41. ^a, ^b van Leeuwen FXR, den Tonkelaar EM, van Logten MJ (1983). "Toxicity of sodi um bromide in rats: Effects on endocrine system and reproduction." Food and Ch emical Toxicology. **21**(4):383–389. doi:10.1016/0278-6915(83)90092-3.
42. ^ Van Leeuwen FXR, Hanemaaijer R, Loeber JG (1988). "The Effect of Sodium Bro mide on Thyroid Function." In: Archives of Toxicology Supplementa. **12**:93–97. do i:10.1007/978-3-642-73113-6_14.
43. ^ Pavelka S, Babický A, Vobecký M, Lener J (2001). "Effect of High Bromide Levels in the Organism on the Biological Half-life of Iodine in the Rat." Biological Trace Element Research. **82**(1-3):125–132. doi:10.1385/bter:82:1-3:125.
44. ^ Buchberger W, Holler W, Winsauer K (1990). "Effects of sodium bromide on the bi osynthesis of thyroid hormones and brominated/iodinated thyronines." J Trace El em. **4**(1):25–30.
45. ^a, ^b Malik R, Hodgson H (2002). "The relationship between the thyroid gland and the liver." QJM. **95**(9):559–569. doi:10.1093/qjmed/95.9.559.

46. ^De Groef B, Grommen SVH, Darras VM (2008). "The chicken embryo as a model for developmental endocrinology: Development of the thyrotropic, corticotropic, and somatotropic axes." Mol Cell Endocrinol. **293**(1-2):17–24. doi:10.1016/j.mce.2008.06.002.
47. a, bDu Toit J, Casey NH (2010). "Effect of bromine and iodine in drinking water on production parameters of broilers." S Afr J Anim Sci. **40**(4):301–310. doi:10.4314/sajas.v40i4.65238.
48. ^Lucht HL, Casey NH (2019). "Prevalence of bromide in groundwater in selected regions in South Africa." Water SA. **45**(3):464–468. doi:10.17159/wsa/2019.v45.i3.6743.
49. ^Mamabolo MC, Meyer JA, Casey NH (2009). "Effects of total dissolved solids on the accumulation of Br, As and Pb from drinking water in tissues of selected organs in broilers." S Afr J Anim Sci. **39**(5):169–172.
50. a, bVobecký M, Pavelka S, Babický A (2005). "Bromide transfer through mother's milk and its impact on the suckling rat." Biol Trace Elem Res. **103**(1):37–48. doi:10.1385/BTER:103:1:037.
51. ^Buchberger W (1988). "Investigations into lactoperoxidase-catalysed bromination of tyrosine and thyroglobulin." Journal of Chromatography B: Biomedical Sciences and Applications. **432**:57–63. doi:10.1016/S0378-4347(00)80633-7.
52. ^Darras VM, Van Herck SL, Heijlen M, De Groef B (2011). "Thyroid hormone receptors in two model species for vertebrate embryonic development: chicken and zebrafish." J Thyroid Res. **2011**:402320. doi:10.4061/2011/402320.
53. ^Salvatore D, Simonides WS, Dentice M, Zavacki AM, Larsen PR (2014). "Thyroid hormones and skeletal muscle - new insights and potential implications." Nat Rev Endocrinol. **10**(4):206–214. doi:10.1038/nrendo.2013.238.
54. ^Cabello G, Wrutniak C (1989). "Thyroid hormone and growth: relationships with growth hormone effects and regulation." Reprod Nutr Dev. **29**(4):387–402. doi:10.1051/rnd:19890401.
55. ^Mohammadalipour R, Rahmani HR, Jahanian R, Riasi A, Mohammadalipour M, Nili N (2017). "Effect of early feed restriction on physiological responses, performance and ascites incidence in broiler chickens raised in normal or cold environment." Animal. **11**(2):219–226. doi:10.1017/s1751731116001555.
56. a, bHarvey CB, Williams GR (2002). "Mechanism of thyroid hormone action." Thyroid. **12**(6):441–446. doi:10.1089/105072502760143791.
57. a, bAl-Rukibat RK, Al-Zghoul MB, Hananeh WM, Al-Natour MQ, Abu-Basha EA (2017). "Thermal manipulation during late embryogenesis: Effect on body weight and temperature, thyroid hormones, and differential white blood cell counts in broiler chickens." Poultry Science. **96**(1):234–240. doi:10.3382/ps/pew298.

Declarations

Funding: National Research Foundation, South Africa, incentive grant to NHC, reference: PR-IFR180205310035/UID96806 and University of Pretoria Physiology Grant: NHC, reference A09038

Potential competing interests: No potential competing interests to declare.